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(54) **CERAMIC-TO-METAL TURBINE SHAFT ATTACHMENT**

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CPC F01D 5/022; F01D 5/026; F01D 5/063; F01D 11/18; F01D 19/02; F01D 25/16; F02B 73/00

See application file for complete search history.

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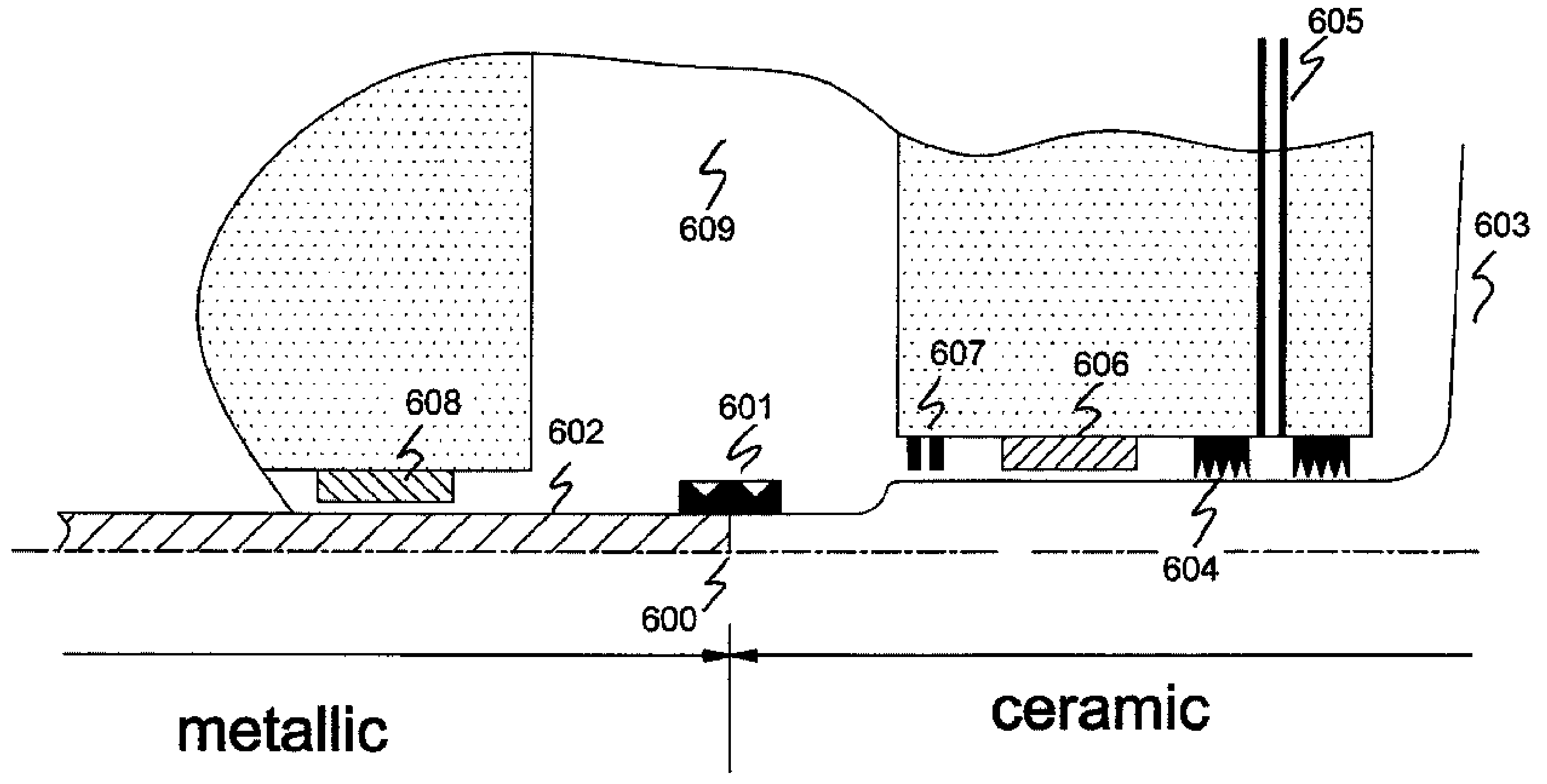
(57) **ABSTRACT**

A metallic-ceramic joint for a turbo-compressor spool is disclosed. A temperature-limited joint is moved from outside the bearings to between the bearings and near the center of the shaft joining the turbine and compressor. This placement can lower the temperature at and around the joint and reduces the sharp gradient (and associated thermal stress) naturally occurring between the turbine rotor and the cooler joint. The bearing closest to the compressor can be an oil bearing and the bearing closest to the turbine an air bearing. The bearing closest to the compressor and the bearing closest to the turbine can both be an oil bearing. The bearing closest to the compressor and the bearing closest to the turbine can both be an air bearing. Moving the metallic-ceramic joint between the bearings can provide sufficient isolation to enable the all-air bearing solution.

28 Claims, 8 Drawing Sheets



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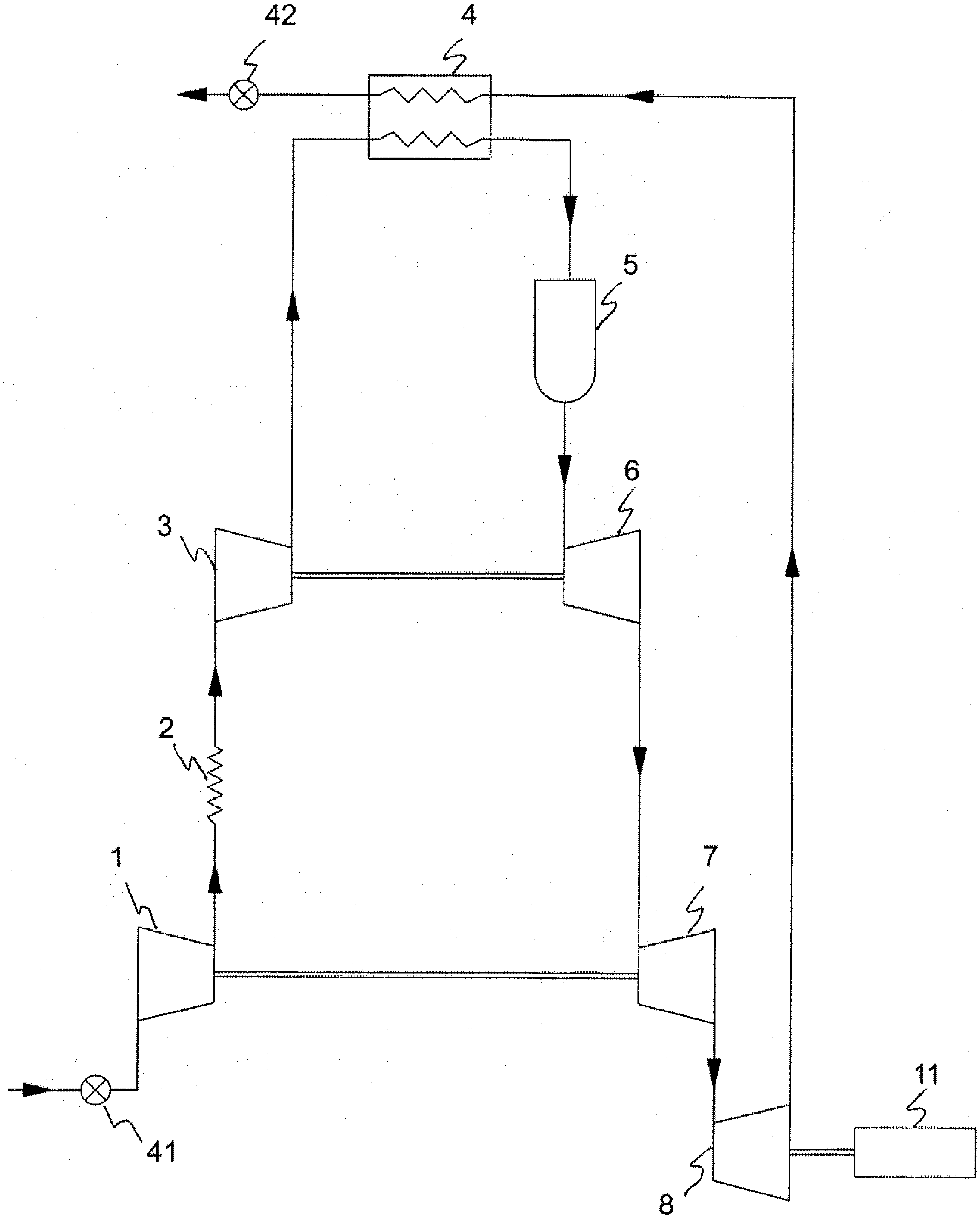

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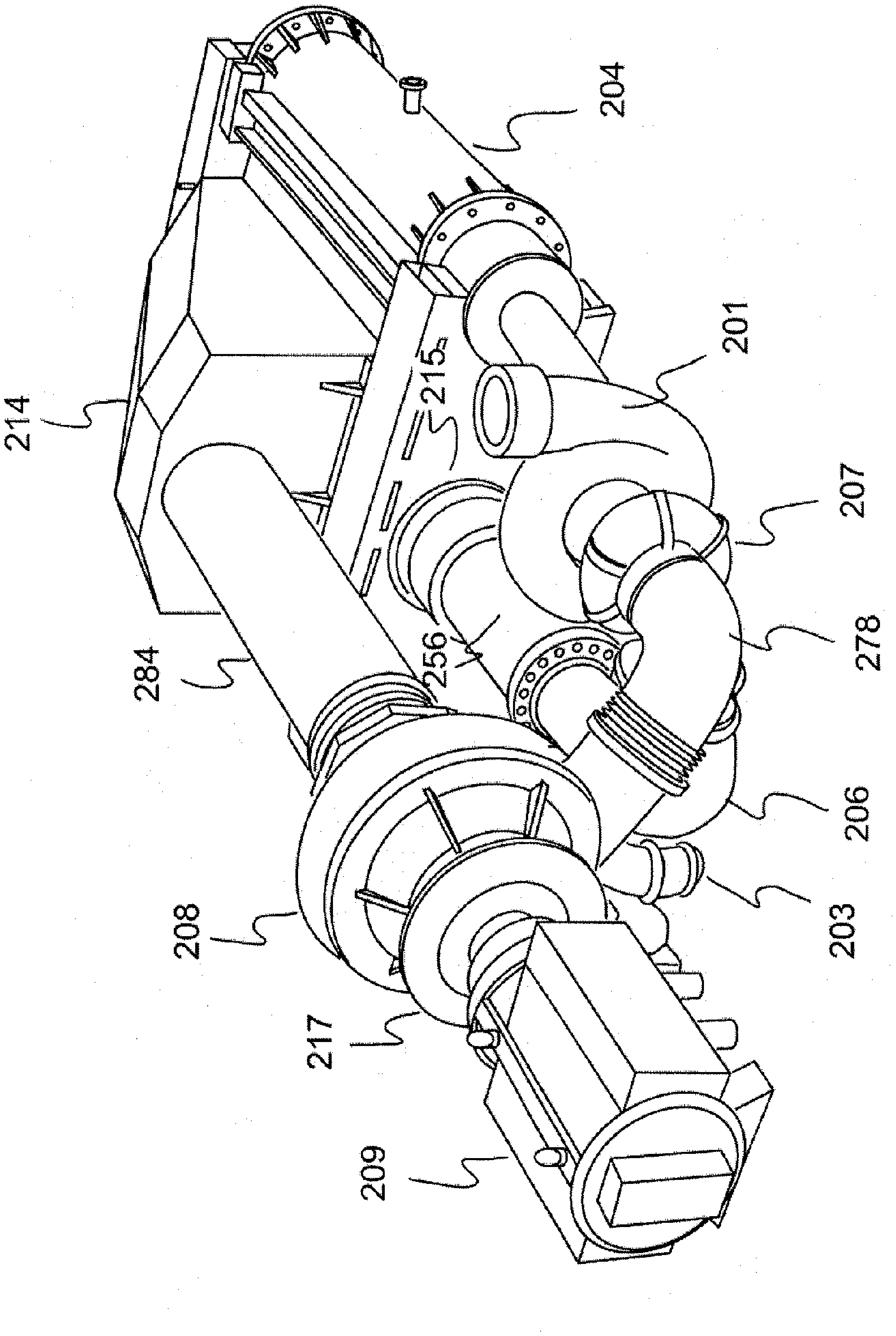

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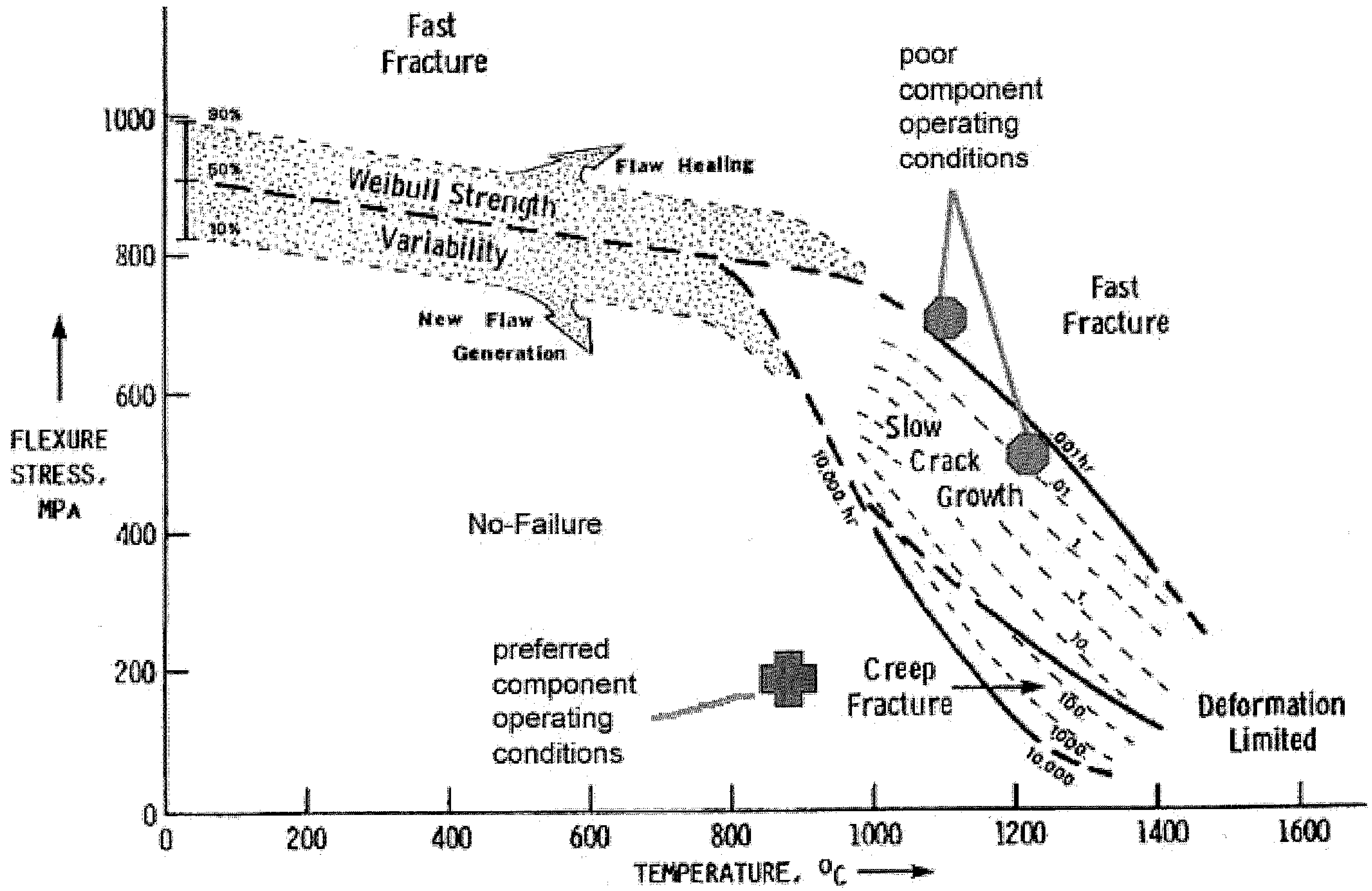
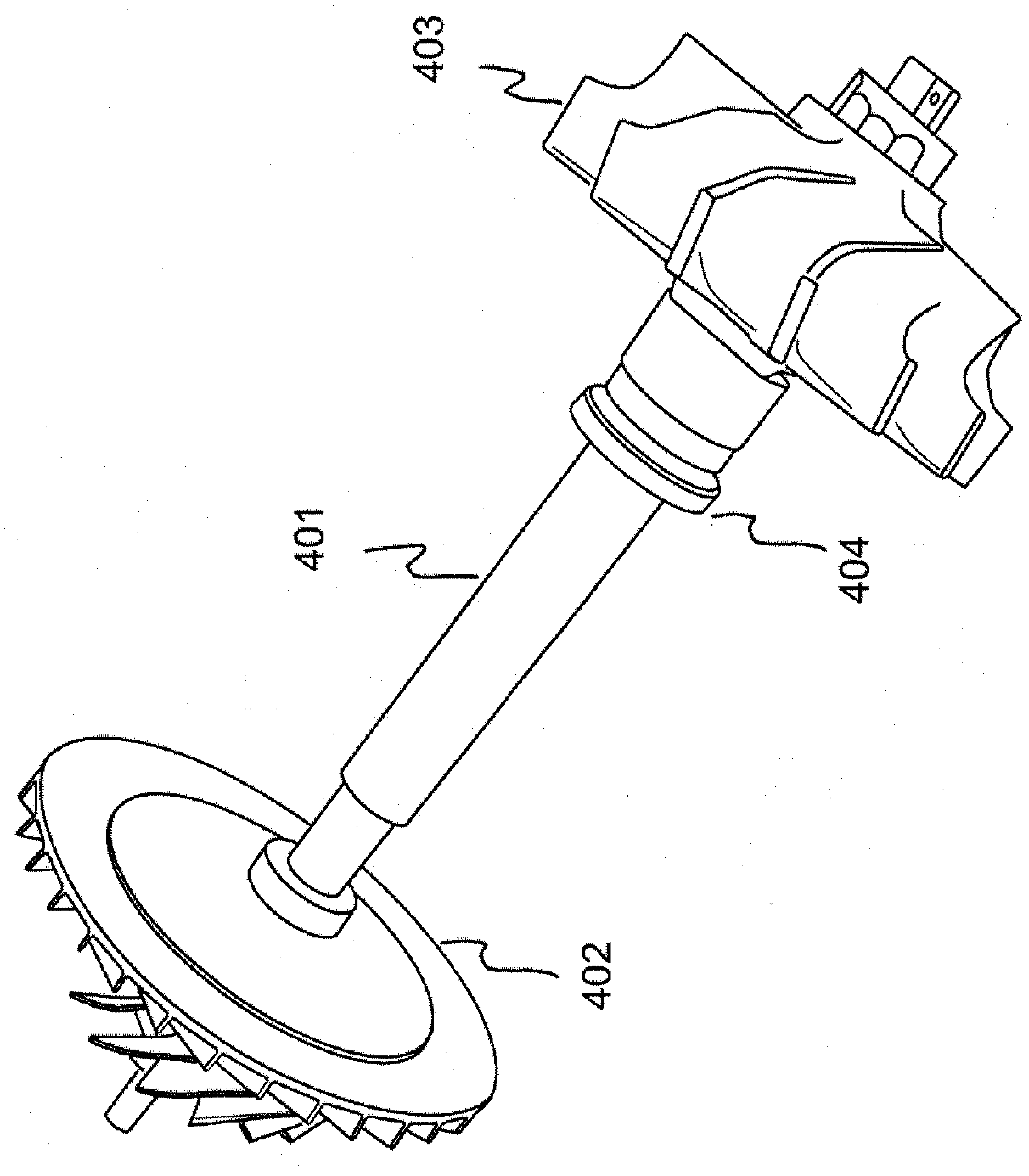

Fast
Fracture
poor
component
operating
conditions
Fast
Fracture
90%
50%
10%
Weibull Strength
Variability
Flaw Healing
New Flaw
Generation
Slow
Crack
Growth
.001 hr
.01
.1
1
10
100
1000
10,000
10,000 hr
No-Failure
preferred
component
operating
conditions
Creep
Fracture
Deformation
Limited
FLEXURE
STRESS,
MPA
1000
800
600
400
200
0
0
200
400
600
800
1000
1200
1400
1600
TEMPERATURE, °C

Figure 3



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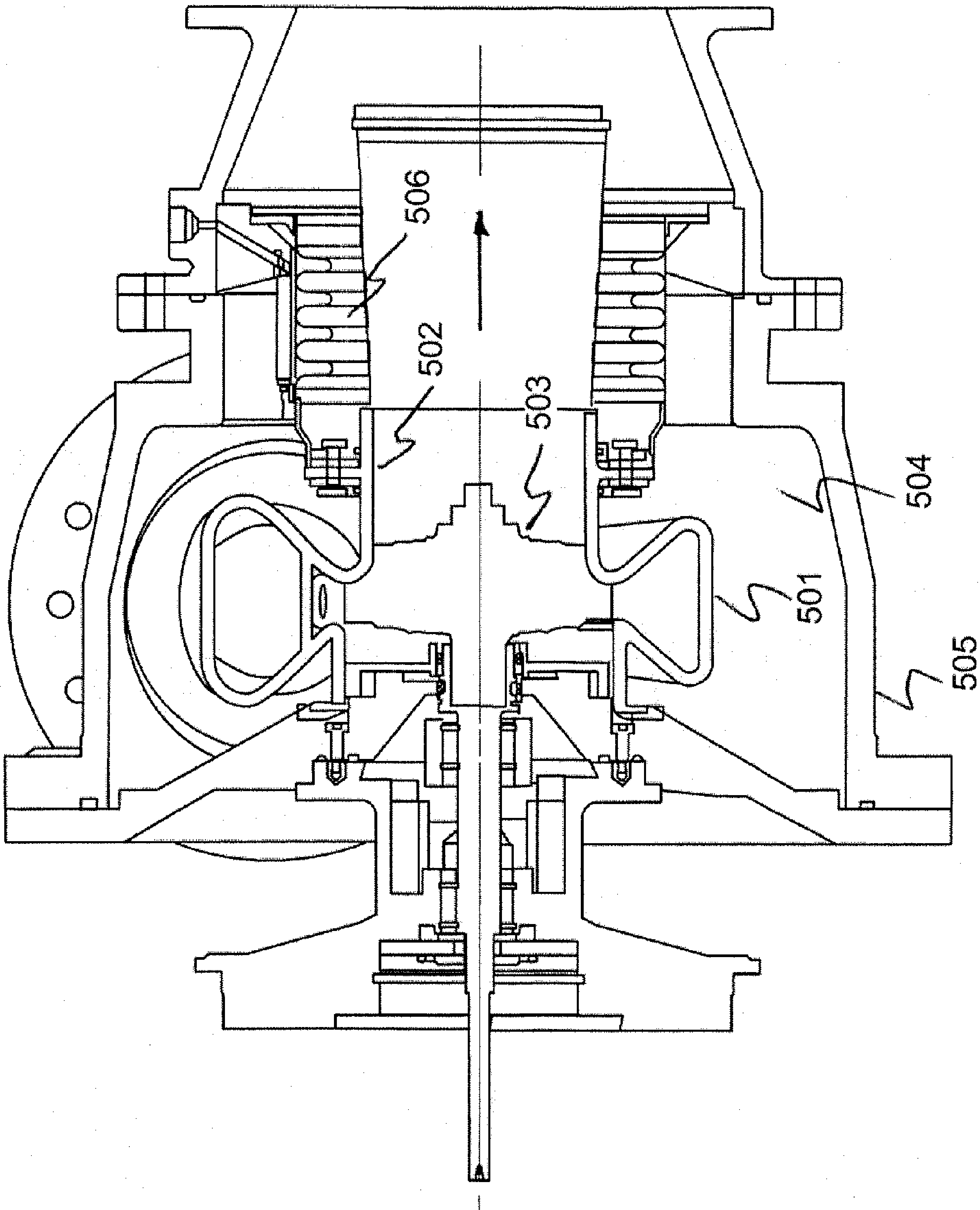

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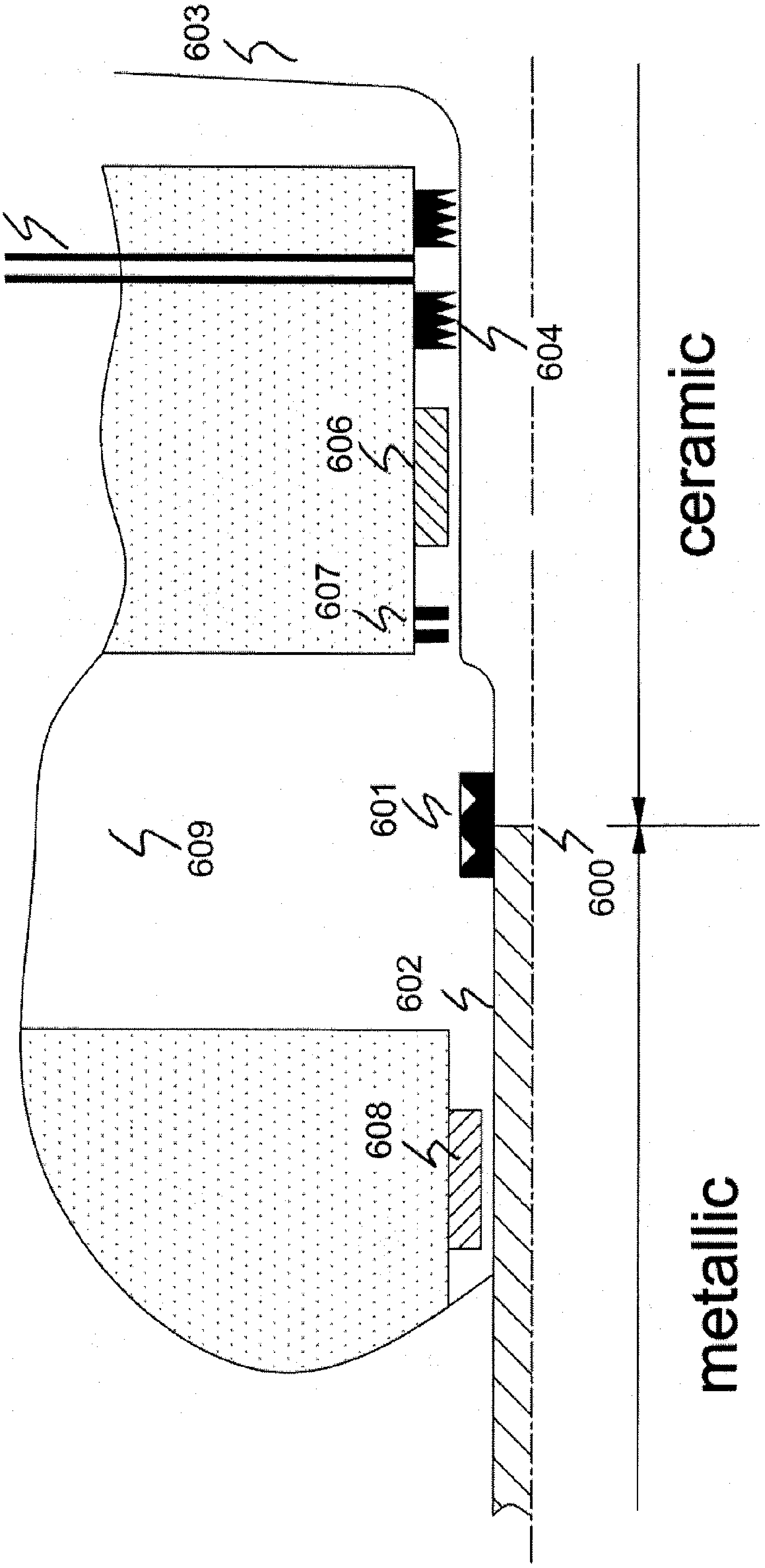

Figure 6

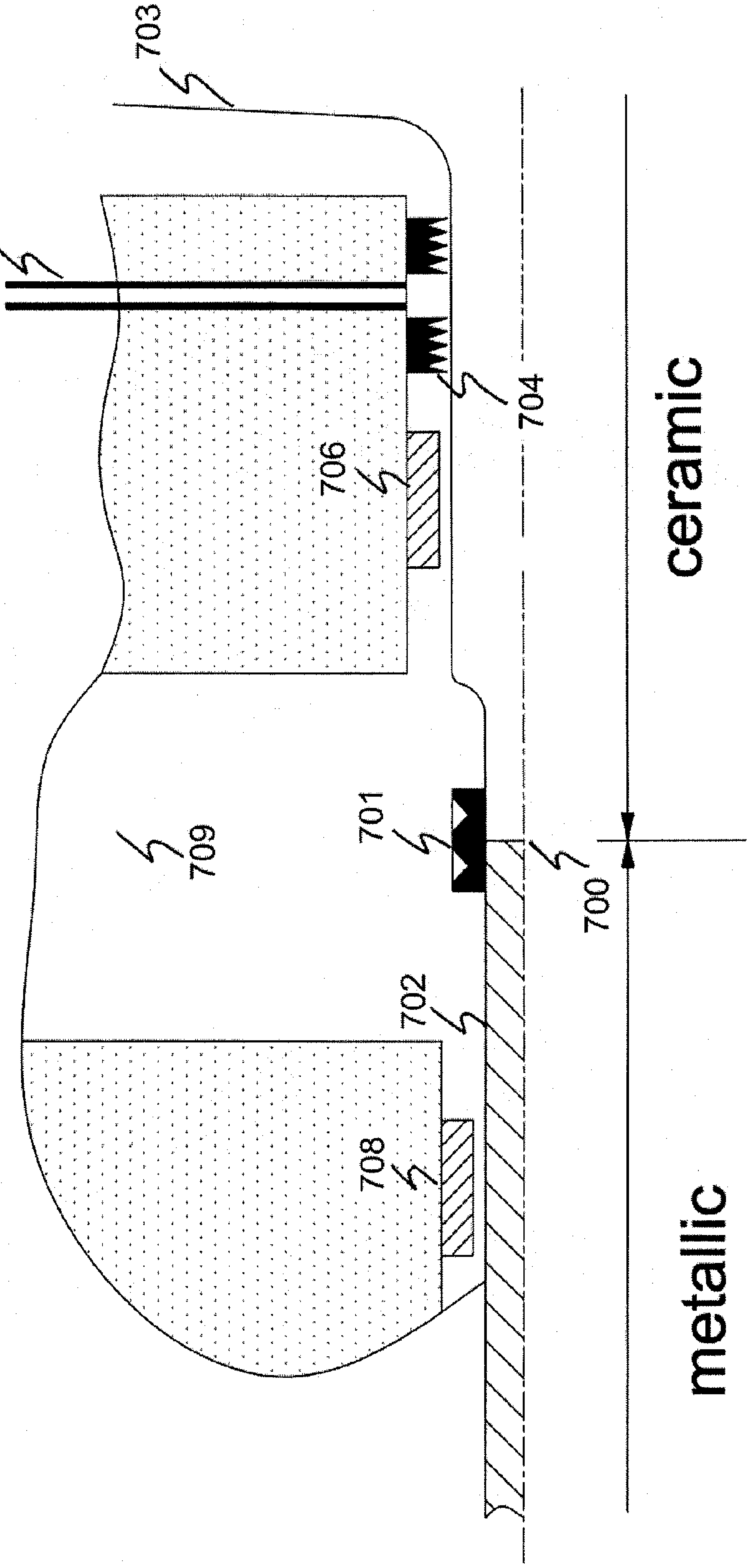

Figure 7

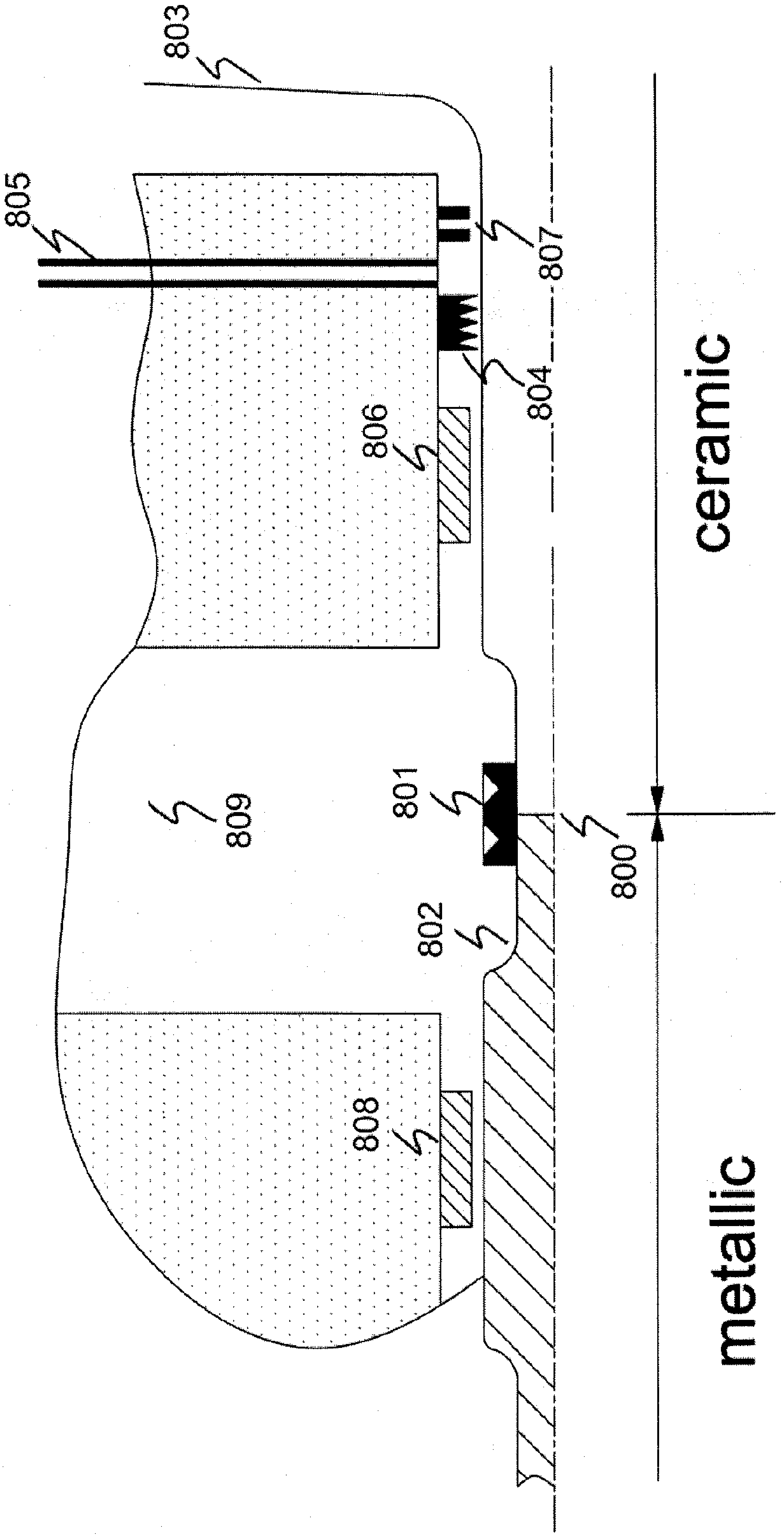

Figure 8

CERAMIC-TO-METAL TURBINE SHAFT ATTACHMENT

CROSS REFERENCE TO RELATED APPLICATION

The present application claims the benefits, under 35 U.S.C. §119(e), of U.S. Provisional Application Ser. No. 61/488,575 entitled "Ceramic-to-Metal Turbine Shaft Attachment" filed on May 20, 2011, which is incorporated herein by reference.

FIELD

This disclosure relates generally to the field of vehicle propulsion and power generation and more specifically to an apparatus attaching a ceramic turbine rotor to a metal shaft.

BACKGROUND

There is a growing requirement for alternate fuels for vehicle propulsion and power generation. These include fuels such as natural gas, bio-diesel, ethanol, butanol, hydrogen and the like. Means of utilizing fuels needs to be accomplished more efficiently and with substantially lower carbon dioxide emissions and other air pollutants such as NOxs.

The gas turbine or Brayton cycle power plant has demonstrated many attractive features which make it a candidate for advanced vehicular propulsion and power generation. Gas turbine engines have the advantage of being highly fuel flexible and fuel tolerant. Additionally, these engines burn fuel at a lower temperature than reciprocating engines so produce substantially less NOx per mass of fuel burned.

The efficiency of gas turbine engines can be improved and engine size can be further reduced by increasing the pressure and temperature developed in the combustor while still remaining well below the temperature threshold of significant NOx production. This can be done using a conventional metallic combustor or a thermal reactor to extract energy from the fuel. As combustor temperature and pressure are raised, new requirements are generated in other components, such as the recuperator and compressor-turbine spools.

In a high efficiency gas turbine engine, the turbine adjacent to the combustor may have a ceramic rotor or it may be an all-ceramic turbine (volute, rotor, rotor shroud). The ceramic rotor is typically attached to a shaft which in turn is usually attached to a compressor which is comprised of a metallic rotor because the compressor blades see much lower temperatures than the turbine blades. The ceramic-to-metal attachment joint represents one of an important feature that, if not designed correctly, can limit the allowable operating temperature of the turbine rotor especially in small turbo-compressor spools such as used in turbo-chargers and microturbines. Most prior art joints are limited to operating temperatures below 800° K. The objective of achieving increased efficiency is pushing the rotor temperatures to levels approaching 1,400° K and, in the future, higher. In the prior art, this joint is typically located close to the turbine rotor, thereby requiring aggressive cooling to maintain the allowable temperature at and around the joint. The steep thermal gradient also creates an area of elevated thermal stress at and around the joint.

There remains a need for a joint design that will allow increased combustor temperatures which, in turn, can improve overall engine efficiency and reduce engine size while maintaining very low levels of NOx production.

SUMMARY

These and other needs are addressed by the various embodiments and configurations of the present disclosure which are directed generally to gas turbine engine systems and specifically to moving the temperature-limited joint to a location between the bearings near the center of the shaft joining the turbine and compressor. This placement lowers the temperature at and around the joint and reduces the sharp gradient (and associated thermal stress) which naturally occurs between the turbine rotor and the cooler joint. This requires a large outside diameter bearing on the turbine side so that it can be assembled. It is also anticipated that the ceramic turbine stub shaft needs to be relatively large in diameter relative to the steel shaft to have the proper stiffness.

In a first configuration the bearing closest to the compressor is an oil bearing and the bearing closest to the turbine is an air bearing.

In another configuration the bearing closest to the compressor is an oil bearing and the bearing closest to the turbine is also an oil bearing.

In yet another configuration the bearing closest to the compressor is an air bearing and the bearing closest to the turbine is also an air bearing. This all-air bearing configuration for the ceramic turbine may be difficult, since air is not as good as oil for cooling. Moving the metallic-ceramic joint between the bearings may provide sufficient isolation to enable the all-air bearing solution.

In various configurations, one or more of the following elements are employed:

1. Relocation of the metallic-ceramic joint substantially further away from the hot turbine gases to substantially reduce the thermal gradient and the thermal stress on the joint.
2. Relocating the joint on the other side of the bearing closest to the turbine.
3. Increasing the diameter of the ceramic shaft coming off the ceramic rotor and using a short, smooth transition down to the diameter of the metallic shaft.
4. In place of the ceramic shaft being inserted into a counterbore in the metallic shaft, the diameter of the ceramic and metallic shaft are the same. Brazing and the use of a connecting sleeve are used to form a strong joint with the required stiffness.
5. Relocating the joint so that either an all-oil bearing; an all-air-bearing; or a combination air and oil bearing system can be used.

In one embodiment, an engine is comprised of a plurality of turbo-compressor spool assemblies, each turbo-compressor spool assembly comprising a compressor and a turbine attached by a common shaft and a first of the turbo-compressor spool assemblies is in fluid communication with a second of the turbo-compressor spool assemblies, at least one of the common shafts of a selected turbo-compressor spool assembly comprising a metallic compressor rotor and a ceramic turbine rotor connected by a metallic-to-ceramic attachment joint and a first bearing being positioned adjacent to the metallic compressor rotor and a second bearing adjacent to the ceramic turbine rotor; a free power turbine driven by a gas flow output by at least one of the turbo-compressor assemblies; and a combustor operable to combust a fuel and a gas output by one of the plurality of turbo-compressor spool assemblies, wherein: when the engine is in operation, the ceramic turbine rotor of the selected turbo-compressor spool assembly operates in a no-failure regime of the ceramic material; the ceramic-to-metallic attachment joint is located on the common shaft of the selected turbo-compressor spool assembly to be in a no-failure regime of the ceramic material, the location of the metallic-to-ceramic attachment joint being positioned between the first and second bearings on the common shaft, and when the engine is in operation, the metallic-to-ceramic attachment joint operates at a temperature of no more than about 800° K.

In another embodiment, an engine is comprised of a plurality of turbo-compressor spool assemblies, each turbo-compressor spool assembly comprising a compressor and a turbine attached by a common shaft and a first of the turbo-compressor spool assemblies is in fluid communication with a second of the turbo-compressor spool assemblies; a free power turbine driven by a gas flow output by at least one of the turbo-compressor assemblies; and a combustor operable to combust a fuel and a gas output by one of the plurality of turbo-compressor spool assemblies, wherein a selected turbo-compressor spool assembly comprises a metallic compressor rotor and a ceramic turbine rotor connected by a metallic-to-ceramic attachment joint, wherein a first and second bearings are located along a common shaft of the selected turbo-compressor spool assembly, and wherein at least one of the following is true: (i) a turbine rotor of a selected turbo-compressor spool assembly operates in a no-failure regime of the ceramic material and the metallic-to-ceramic attachment joint is located to be in a no-failure regime of the ceramic material; (ii) the metallic-to-ceramic attachment joint is located between the first and second bearings; (iii) a ceramic portion of the common shaft has a length of at least about 40% of a length of the shaft; and (iv) respective diameters of the ceramic portion and a metallic portion of the common shaft are substantially the same in the vicinity of the metallic-to-ceramic attachment joint.

A method is disclosed, comprising providing a gas turbine engine, the gas turbine engine comprising a turbo-compressor spool assembly, the turbo-compressor spool assembly comprising a compressor and a turbine attached by a common shaft, a free power turbine driven by a gas flow output by the turbo-compressor assembly, and a combustor operable to combust a fuel and a gas output by the turbo-compressor spool assembly, the compressor comprising a metallic compressor rotor and the turbine comprising a ceramic turbine rotor connected by a metallic-to-ceramic attachment joint; and when the gas turbine engine is in operation, maintaining the turbine rotor and the metallic-to-ceramic attachment joint in a no-failure regime of the ceramic material.

The following definitions are used herein:

As used herein, "at least one", "one or more", and "and/or" are open-ended expressions that are both conjunctive and disjunctive in operation. For example, each of the expressions "at least one of A, B and C", "at least one of A, B, or C", "one or more of A, B, and C", "one or more of A, B, or C" and "A, B, and/or C" means A alone, B alone, C alone, A and B together, A and C together, B and C together, or A, B and C together.

A bellows is a flexible or deformable, expandable and/or contractable, container or enclosure. A bellows is typically a container which is deformable in such a way as to alter its volume. A bellows can refer to a device for delivering pressurized air in a controlled quantity to a controlled location.

A ceramic is an inorganic, nonmetallic solid prepared by the action of heating and cooling. Ceramic materials may have a crystalline or partly crystalline structure, or may be amorphous (e.g., a glass).

An engine is a prime mover and refers to any device that uses energy to develop mechanical power, such as motion in some other machine. Examples are diesel engines, gas turbine engines, microturbines, Stirling engines and spark ignition engines.

A free power turbine as used herein is a turbine which is driven by a gas flow and whose rotary power is the principal mechanical output power shaft. A free power turbine is not connected to a compressor in the gasifier section, although the free power turbine may be in the gasifier section of the gas turbine engine. A power turbine may also be connected to a compressor in the gasifier section in addition to providing rotary power to an output power shaft.

A gas turbine engine as used herein may also be referred to as a turbine engine or microturbine engine. A microturbine is commonly a sub category under the class of prime movers called gas turbines and is typically a gas turbine with an output power in the approximate range of about a few kilowatts to about 700 kilowatts. A turbine or gas turbine engine is commonly used to describe engines with output power in the range above about 700 kilowatts. As can be appreciated, a gas turbine engine can be a microturbine since the engines may be similar in architecture but differing in output power level. The power level at which a microturbine becomes a turbine engine is arbitrary and the distinction has no meaning as used herein.

A gasifier is a turbine-driven compressor in a gas turbine engine dedicated to compressing air that, once heated, is expanded through a free power turbine to produce

A prime power source refers to any device that uses energy to develop mechanical or electrical power, such as motion in some other machine. Examples are diesel engines, gas turbine engines, microturbines, Stirling engines, spark ignition engines and fuel cells.

A heat exchanger is a device that allows heat energy from a hotter fluid to be transferred to a cooler fluid without the hotter fluid and cooler fluid coming in contact. The two fluids are typically separated from each other by a solid material, such as a metal, that has a high thermal conductivity.

The term means shall be given its broadest possible interpretation in accordance with 35 U.S.C., Section 112, Paragraph 6. Accordingly, a claim incorporating the term "means" shall cover all structures, materials, or acts set forth herein, and all of the equivalents thereof. Further, the structures, materials or acts and the equivalents thereof shall include all those described in the summary of the invention, brief description of the drawings, detailed description, abstract, and claims themselves.

A metallic material is a material containing a metal or a metallic compound. A metal refers commonly to alkali metals, alkaline-earth metals, radioactive and nonradioactive rare earth metals, transition metals, and other metals.

The no-failure regime of a ceramic material, as used herein, refers to the region of a flexural strength versus temperature graph for ceramic materials wherein both the flexural stress and temperature are low enough that the ceramic material has a very low probability of failure and has a lifetime of a very large number of flexural and/or thermal cycles. Operation of the ceramic material in the no-failure regime means that the combination of maximum flexural stress and maximum temperature do not approach a failure limit such as the Weibull strength variability regime, the fast fracture regime, the slow crack growth regime or the creep fracture regime as illustrated in FIG. **3**. When the ceramic material approaches or enters any of these failure regimes, then the probability of failure is increased precipitously and the lifetime to failure of the component is reduced precipitously. This applies to ceramic components that are manufactured within their design specifications from ceramic materials that are also within their design specifications. Typically, the no-failure regime of the ceramics used herein exists at operating temperatures of no more than about 1,550° K, more typically of no more than about

1,500° K, and even more typically of no more than about 1,400° K. Common maximum flexural strengths for the no-failure regime of the ceramics used herein are about 250 MPa and more commonly about 175 MPa.

Power density as used herein is power per unit volume (watts per cubic meter).

A recuperator is a heat exchanger dedicated to returning exhaust heat energy from a process back into the process to increase process efficiency. In a gas turbine thermodynamic cycle, heat energy is transferred from the turbine discharge to the combustor inlet gas stream, thereby reducing heating required by fuel to achieve a requisite firing temperature.

Regenerative braking is the same as dynamic braking except the electrical energy generated is captured in an energy storage system for future use.

Specific power as used herein is power per unit mass (watts per kilogram).

Spool refers to a group of turbo machinery components on a common shaft.

A thermal energy storage module is a device that includes either a metallic heat storage element or a ceramic heat storage element with embedded electrically conductive wires. A thermal energy storage module is similar to a heat storage block but is typically smaller in size and energy storage capacity.

A thermal oxidizer is a type of combustor comprised of a matrix material which is typically a ceramic and a large number of channels which are typically circular in cross section. When a fuel-air mixture is passed through the thermal oxidizer, it begins to react as it flows along the channels until it is fully reacted when it exits the thermal oxidizer. A thermal oxidizer is characterized by a smooth combustion process as the flow down the channels is effectively one-dimensional fully developed flow with a marked absence of hot spots.

A thermal reactor, as used herein, is another name for a thermal oxidizer.

A turbine is a rotary machine in which mechanical work is continuously extracted from a moving fluid by expanding the fluid from a higher pressure to a lower pressure. The simplest turbines have one moving part, a rotor assembly, which is a shaft or drum with blades attached. Moving fluid acts on the blades, or the blades react to the flow, so that they move and impart rotational energy to the rotor.

Turbine Inlet Temperature (TIT) as used herein refers to the gas temperature at the outlet of the combustor which is closely connected to the inlet of the high pressure turbine and these are generally taken to be the same temperature.

A turbo-compressor spool assembly as used herein refers to an assembly typically comprised of an outer case, a radial compressor, a radial turbine wherein the radial compressor and radial turbine are attached to a common shaft. The assembly also includes inlet ducting for the compressor, a compressor rotor, a diffuser for the compressor outlet, a volute for incoming flow to the turbine, a turbine rotor and an outlet diffuser for the turbine. The shaft connecting the compressor and turbine includes a bearing system.

A volute is a scroll transition duct which looks like a tuba or a snail shell. Volutes may be used to channel flow gases from one component of a gas turbine to the next. Gases flow through the helical body of the scroll and are redirected into the next component. A key advantage of the scroll is that the device inherently provides a constant flow angle at the inlet and outlet. To date, this type of transition duct has only been successfully used on small engines or turbochargers where the geometrical fabrication issues are less involved.

Weibull statistics are used in characterizing the strength of brittle materials such as most ceramics and relate a series of bending strength measurements to the probability of failure. Weibull statistics include a strength modulus called Weibull modulus.

BRIEF DESCRIPTION OF THE DRAWINGS

The disclosure may take form in various components and arrangements of components, and in various steps and arrangements of steps. The drawings are only for purposes of illustrating the preferred embodiments and are not to be construed as limiting the disclosure. In the drawings, like reference numerals refer to like or analogous components throughout the several views.

FIG. **1** is prior art schematic of the component architecture of a multi-spool gas turbine engine.

FIG. **2** is a line drawing of a gas turbine suitable for long haul trucks. This is prior art.

FIG. **3** is a stress-temperature map showing ceramic failure regimes.

FIG. **4** is a schematic of a prior art turbo-compressor spool showing a metallic compressor rotor and a ceramic turbine rotor.

FIG. **5** is a schematic of a prior art gas turbine compressor/turbine spool comprising a ceramic rotor, volute and shroud.

FIG. **6** shows a general configuration of an air and oil hybrid bearing system with a ceramic-to-metal attachment joint of the present disclosure.

FIG. **7** shows a general configuration of an all-oil bearing system with a ceramic-to-metal attachment joint of the present disclosure.

FIG. **8** shows a general configuration of an all-air bearing system with a ceramic-to-metal attachment joint of the present disclosure.

DETAILED DESCRIPTION

Exemplary Gas Turbine Engine

An exemplary engine is a high efficiency gas turbine engine. It typically has lower NOx emissions, is more fuel flexible and has lower maintenance costs than comparable reciprocating engines. For example, an intercooled recuperated gas turbine engine in the range of about 10 kW to about 750 kW is available with thermal efficiencies above 40%. A schematic of an intercooled, recuperated gas turbine engine is shown in FIG. **1**.

FIG. **1** is prior art schematic of the component architecture of a multi-spool gas turbine engine. Gas is ingested into a low pressure compressor **1**. The outlet of the low pressure compressor **1** passes through an intercooler **2** which removes a portion of heat from the gas stream at approximately constant pressure. The gas then enters a high pressure compressor **3**. The outlet of high pressure compressor **3** passes through a recuperator **4** where some heat from the exhaust gas is transferred, at approximately constant pressure, to the gas flow from the high pressure compressor **3**. The further heated gas from recuperator **4** is then directed to a combustor **5** where a fuel is burned, adding heat energy to the gas flow at approximately constant pressure. The gas emerging from the combustor **5** then enters a high pressure turbine **6** where work is done by the turbine to operate the high pressure compressor **3**. The gas exiting from the high pressure turbine **6** then enters a low pressure turbine **7** where work is done by the turbine to operate the low pressure compressor **1**. The gas exiting from the low pressure turbine **7** then enters a free power turbine **8**. The shaft of the free power turbine, in turn, drives a transmission **11** which may be an electrical, mechanical or hybrid transmission for a vehicle. Alternately, the shaft of the free power turbine can drive an electrical generator or alternator. This engine design is described, for example, in U.S. patent application Ser. No. 12/115,134 filed May 5, 2008, entitled "Multi-Spool Intercooled Recuperated Gas Turbine", which is incorporated herein by this reference.

As can be appreciated, the engine illustrated in FIG. **1** can have additional components (such as for example a re-heater between the high pressure and low pressure turbines) or can have fewer components (such as for example a single compressor-turbine spool, or no free power turbine but shaft power coming off the low pressure turbine spool).

A gas turbine engine is an enabling engine for efficient multi-fuel use and, in particular, this engine can be configured to switch between fuels while the engine is running and the vehicle is in motion (on the fly). In addition, a gas turbine engine can be configured to switch on the fly between liquid and gaseous fuels or operate on combinations of these fuels. This is possible because combustion in a gas turbine engine is continuous (as opposed to episodic such as in a reciprocating piston engine) and the important fuel parameter is the specific energy content of the fuel (that is, energy per unit mass) not its cetane number or octane rating. The cetane number (typically for diesel fuels and compression ignition) or octane rating (typically for gasoline fuels and spark ignition) are important parameters in piston engines for specifying fuel ignition properties.

The gas turbine engine such as shown schematically in FIG. **2** enables a multi-fuel strategy. This engine is prior art although even more efficient multi-fuel configurations will require innovative modifications to components and subcomponents. This is an example of a 375 kW engine that uses intercooling and recuperation to achieve high operating efficiencies (40% or more) over a substantial range of vehicle operating speeds. This compact engine is suitable for light to heavy trucks. Variations of this engine design are suitable for smaller vehicles as well as applications such as, for example, marine, rail, agricultural and power-generation. One of the principal features of this engine is its fuel flexibility and fuel tolerance. This engine can operate on any number of liquid fuels (gasoline, diesel, ethanol, methanol, butanol, alcohol, bio diesel and the like) and on any number of gaseous fuels (compressed or liquid natural gas, propane, hydrogen and the like). This engine may also be operated on a combination of fuels such as mixtures of gasoline and diesel or mixtures of diesel and natural gas. Switching between these fuels is generally a matter of switching fuel injection systems and/or fuel mixtures.

This engine operates on the Brayton cycle and, because combustion is continuous, the peak operating temperatures are substantially lower than comparably sized piston engines operating on either an Otto cycle or Diesel cycle. This lower peak operating temperature results in substantially less NOx emissions generated by the gas turbine engine shown in FIG. **2**. This figure shows a load device **209**, such as for example a high speed alternator, attached via a reducing gearbox **217** to the output shaft of a free power turbine **208**. A cylindrical duct **284** delivers the exhaust from free power turbine **208** to a plenum **214** which channels exhaust through the hot side of recuperator **204**. Low pressure compressor **201** receives its inlet air via a duct (not shown) and sends compressed inlet flow to an intercooler (also not shown). The flow from the intercooler is sent to high pressure compressor **203** which is partially visible underneath free power turbine **208**. As described previously, the compressed flow from high pressure compressor **203** is sent to the cold side of recuperator **204** and then to a combustor which is contained inside recuperator **204**. The flow from combustor **215** (whose outlet end is just visible) is delivered to high pressure turbine **206** via cylindrical duct **256**. The flow from high pressure turbine **206** is directed through low pressure turbine **207**. The expanded flow from low pressure turbine **207** is then delivered to free power turbine **208** via a cylindrical elbow **278**.

This engine has a relatively flat efficiency curve over wide operating range (from about 20% of full power to about 85% of full power). It also has a multi-fuel capability with the ability to change fuels on the fly as described in U.S. patent application Ser. No. 13/090,104 filed Apr. 19, 2011 entitled "Multi-Fuel Vehicle Strategy" which is incorporated herein by reference.

Ceramics Used in Gas Turbines

FIG. **3** is a stress-temperature map illustrating failure regimes for typical ceramic materials. This graphic shows that when flexure stress and temperature experienced by a ceramic component are high, the component operates in the fast fracture regime and the ceramic component lifetime would be expected to be unpredictable and typically short. This graphic also shows that when flexure stress and temperature experienced by a ceramic component are low, then the component operates in the no-failure regime and the ceramic component lifetime would be expected to be predictable and typically long. When the flexure stress is high but the temperature is low, then the component operates in a regime characterized by Weibull strength variability. When the flexure stress is low but the temperature is high, then the component operates in a regime characterized by slow crack growth or creep and the ceramic component lifetime would be expected to be somewhat unpredictable and variable.

Some gas turbine engines, especially microturbines, have used ceramic components in prototype situations. These have been used for relatively high temperatures and operated in the slow crack growth region. These engines have experienced failure of the ceramic components. One of the design goals used in the present disclosure is to maintain ceramic component operation well inside the no-failure regime so that incidences of component failure are substantially minimized and component lifetime is substantially maximized. A number of turbochargers have used ceramic components operating in the no-failure region, most notably ceramic rotors.

The following table shows some important properties of ceramics that are typically used for gas turbine components.

TABLE 1

	Alumina	Cordierite	Silicon Carbide	Silicon Nitride	Mullite
Density (kg/m3)	3,700-3,970	2,600	3,210	3,310	2,800
Specific Heat (J/kg/K)	670	1,465	628	712	963
Thermal Conductivity (W/m/K)	24	3	41	27	3.5
Coefficient Thermal Expansion (μm/m/K)	8.39	1.7	5.12	3.14	5.3
Thermal Shock Resistance (ΔT (K))	200-250	500	350-500	750	300

TABLE 1-continued

	Alumina	Cordierite	Silicon Carbide	Silicon Nitride	Mullite
Maximum Use Temperature (K)	3,925	1,645	1,675	1,775	1,975

FIG. **4** is a schematic of a prior art turbo-compressor spool showing a metallic compressor rotor and a ceramic turbine rotor. This figure illustrates a compressor/turbine spool typical of use in a high-efficiency gas turbine operating in the output power range of about 300 to about 750 kW. A metallic compressor rotor **402** and a ceramic turbine rotor **403** are shown attached to the opposite ends of a metal shaft **401**. The ceramic rotor shown here is a 95-mm diameter rotor fabricated from silicon nitride and was originally designed for use in turbocharger applications. As can be seen, the joint **404** between the ceramic rotor and metallic shaft is close to the ceramic rotor and is therefor exposed to high temperatures of the combustion products passing through the turbine. As can be seen, the joint **404** between the ceramic rotor and metallic shaft is close to the ceramic rotor and would typically be between the leftmost oil bearing and the ceramic rotor. The joint **404** is formed by inserting the ceramic shaft stub into a counterbore in the metallic shaft. The joint **404** is about 20 to about 25 mm from the ceramic rotor and is therefore exposed to high temperatures of the gas products passing through the turbine. Typical turbine inlet temperatures for this design are in the range of about 1,250° K to about 1,400° K.

FIG. **5** is schematic of a prior art gas turbine compressor/turbine spool assembly with ceramic and metallic components. This figure was taken from U.S. patent application Ser. No. 13/180,275 entitled "Metallic Ceramic Spool for a Gas Turbine Engine" filed Jul. 11, 2011 which is incorporated herein by reference. FIG. **5** illustrates a turbo-compressor spool with an all-ceramic high pressure turbine section. A ceramic turbine rotor **503** is shown separated by a small clearance gap from a ceramic shroud **502** which is integral with a ceramic volute **501**. The volute, shroud and rotor are housed inside a metal case **504**. The ceramic shroud **502** is also attached to a compliant metallic bellows **506** which is attached to an outer metal case **505**. This configuration is capable of operating safely at turbine inlet temperatures in the approximate range from about 850° K to about 1,400° K. The ceramic rotor may be fabricated from rotor fabricated from silicon nitride. The ceramic shroud and volute can be fabricated from silicon carbide, for example, which has a coefficient of thermal expansion similar to that of silicon nitride used for the rotor. The use of a rotor and volute/shroud fabricated from the same or similar ceramics adequately thus controls radial and axial shroud clearances between the rotor **503** and shroud **502** and maintains high rotor efficiency by controlling the clearance and minimizing parasitic flow leakages between the rotor blade tips and the shroud. This design of a single piece or two piece ceramic volute and shroud for use with a ceramic turbine rotor is preferred if the ceramic material used can be operated well within the no-failure region as shown in FIG. **3**. U.S. patent application Ser. No. 13/180,275 also describes a turbo-compressor spool comprised of ceramic and metallic components and with an active clearance control system.

Present Disclosure

The ceramic-to-metal attachment joint represents an important feature that, if not designed properly, limits the allowable operating temperature of the turbine rotor. Most joints of this type are limited to operating temperatures below 800° K. The drive for increased efficiency is pushing the rotor temperatures to levels approaching 1,400° K and higher. In the prior art, this ceramic-to-metal attachment is typically located close to the turbine rotor (see FIG. **4** for example), thus aggressive cooling is required to maintain the allowable temperature. The steep thermal gradient creates an area of elevated thermal stress.

Moving the temperature-limited joint between the bearings lowers its temperature and reduces the sharp gradient (and associated thermal stress) which naturally occurs between the turbine rotor and the cooler joint. A large outside diameter bearing is required on the turbine side so that it can be assembled. It is also anticipated that the ceramic turbine stub shaft needs to be relatively large in diameter relative to the metallic portion of the shaft to have the proper stiffness.

In the embodiments described herein, one or more of the following configurations are employed:

1. Relocation of the ceramic-metallic joint substantially further away from the hot turbine gases to substantially reduce the thermal gradient and the thermal stress on the joint.
2. Relocating the joint on the other side of the bearing closest to the turbine.
3. Increasing the length and diameter of the ceramic shaft that is an integral part of the ceramic rotor and using a short, smooth transition down to the diameter of the metallic shaft.
4. In place of the ceramic shaft being inserted into a counterbore in the metallic shaft, the diameter of the ceramic and metallic shaft is made the same. Brazing and the use of a connecting sleeve are used to form a strong joint with the required stiffness and ability to transmit the required torque.
5. Relocating the joint so that either an all-oil bearing; an all-air bearing; or a combination air and oil bearing system can be used.

Consider the joint re-design in terms of the stress-temperature map of FIG. **3** which illustrates ceramic failure regimes. In the prior art joint, flexure stress and temperature experienced by the ceramic material in the vicinity of the joint are relatively high and the ceramic material operates near the creep fracture regime where ceramic component lifetime would tend to be somewhat unpredictable and variable. By moving the joint away from the turbine rotor thereby lowering the temperature at the joint, flexure stress would increase and the net result is that the ceramic material near the joint would remain near the creep fracture region and begin to approach the region characterized by Weibull strength variability. By increasing the ceramic shaft diameter and utilizing a sleeve to stiffen the joint, the flexure stress is reduced while temperature is maintained at its lower value. This places the ceramic joint material well within the no-failure regime and the lifetime of the ceramic material around the joint would be expected to be predictable and typically long.

As the turbine inlet temperature is increased over time as part of continued product improvement, the ceramic material in the vicinity of the joint should remain well within the no-failure zone of flexure stress versus temperature. Therefore the present disclosure not only solves a near term problem but is robust enough to maintain a long lifetime for the ceramic material in the vicinity of the metallic-ceramic joint.

FIG. **6** shows a general configuration of an air and oil hybrid bearing system with a ceramic-to-metal attachment joint **600** of the present disclosure. The ceramic-to-metal joint **600** is shown positioned approximately mid-way between the compressor rotor (not shown) and turbine rotor **603** and between an oil bearing **608** on the compressor side and an air bearing **606** on the turbine side. A coupler sleeve **601** is shown around joint **600** between the ceramic and the metallic shaft **602**. The ceramic shaft is also part of the ceramic rotor **603** and is typically made from silicon nitride, silicon carbide, alumina or the like. The metallic shaft is typically fabricated from a high strength, high temperature steel such as for example a stainless steel or an Inconel steel. The metallic portion of the shaft may also be made from other metals such as titanium and even a high strength-high temperature aluminum. The metallic shaft **602** is the same diameter as the end of the ceramic shaft and the ceramic shaft transitions smoothly o a larger diameter to improve shaft stiffness. The ceramic and metallic shafts are typically brazed together to form a strong joint **600**. The coupler sleeve **601** may also be brazed to the outer surface of the metallic and ceramic shafts. The coupler sleeve **601** is typically made from a high strength, high temperature steel such as for example a stainless or an Inconel steel. In the configuration of FIG. **6**, the compressor-side bearing **608** is an oil bearing where oil is forced between the oil bearing and the metallic shaft during operation. Region **609** is filled with an oil mist. The turbine-side bearing **606** is an air bearing where air, typically bled from the compressor air flow, is directed between two labyrinth seals **604** and forced between the air bearing and the ceramic shaft during operation. The compressor bleed **605** is approximately about 2% of the total air flow through its corresponding compressor. The air and oil are separated by a discourager **607**. In FIG. **6**, the ceramic/metallic joint **600** is about 75 mm from the 95-mm diameter turbine rotor and is about 3 to about 4 times as far away from the turbine rotor as the prior art joint shown in FIG. **4**.

FIG. **7** shows a general configuration of an all-oil bearing system with a ceramic-to-metal attachment joint **700** of the present invention. The ceramic-to-metal joint **700** is shown positioned approximately mid-way between the compressor rotor (not shown) and turbine rotor **703** and between an oil bearing **708** on the compressor side and a larger split oil bearing **706** on the turbine side. This latter bearing may be split for assembly. A coupler sleeve **701** is shown around joint **700** between the ceramic and the metallic shafts. The metallic shaft **702** is the same diameter as the end of the ceramic shaft and the ceramic shaft transitions to a larger diameter to improve shaft stiffness. In the configuration of FIG. **7**, the compressor-side bearing **708** is an oil bearing where oil is forced between the oil bearing **708** and the metallic shaft **702** during operation. Region **709** is filled with an oil mist. The turbine-side bearing **706** is also an oil bearing where oil is forced between the oil bearing and the ceramic shaft during operation. Air is typically bled from the compressor air flow and directed between two labyrinth seals **704** and helps prevent oil from leaking into the turbine rotor air flow. In FIG. **7**, the ceramic/metallic joint **700** is about 75 mm from the 95-mm diameter turbine rotor and is about 3 to about 4 times as far away from the turbine rotor as the prior art joint shown in FIG. **4**.

FIG. **8** shows a general configuration of an all-air bearing system with a ceramic-to-metal attachment joint **800** of the present disclosure. The ceramic-to-metal joint **800** is shown positioned approximately mid-way between the compressor rotor (not shown) and turbine rotor **803** and between an air bearing **808** on the compressor side and a similar sized air bearing **806** on the turbine side. One or both bearings may be split for assembly. As shown in FIG. **8**, the metallic shaft **802** has a large diameter section so that the two air bearings can be the same component. A coupler sleeve **801** is shown around the joint **800** between the ceramic and the metallic shafts. The metallic shaft **802** is the same diameter as the end of the ceramic shaft and the ceramic shaft transitions to a larger diameter to improve shaft stiffness. In the configuration of FIG. **8**, the compressor-side bearing **808** is an air bearing where air is forced between the air bearing and the metallic shaft **802** during operation. The turbine-side bearing **806** is also an air bearing where air is forced between the air bearing and the ceramic shaft during operation. Air is typically bled from the compressor air flow and directed between a labyrinth seal **804** and a discourager **807**. In FIG. **8**, the ceramic/metallic joint **800** is about 75 mm from the 95-mm diameter turbine rotor and is about 3 to about 4 times as far away from the turbine rotor as the prior art joint shown in FIG. **4**. Moving the joint to about halfway between the air bearings **806** and **808** is anticipated to provide sufficient isolation to enable this all-air bearing solution.

The disclosure has been described with reference to the preferred embodiments. Modifications and alterations will occur to others upon a reading and understanding of the preceding detailed description. It is intended that the disclosure be construed as including all such modifications and alterations insofar as they come within the scope of the appended claims or the equivalents thereof.

A number of variations and modifications of the disclosures can be used. As will be appreciated, it would be possible to provide for some features of the disclosures without providing others.

The present disclosure, in various embodiments, includes components, methods, processes, systems and/or apparatus substantially as depicted and described herein, including various embodiments, sub-combinations, and subsets thereof. Those of skill in the art will understand how to make and use the present disclosure after understanding the present disclosure. The present disclosure, in various embodiments, includes providing devices and processes in the absence of items not depicted and/or described herein or in various embodiments hereof, including in the absence of such items as may have been used in previous devices or processes, for example for improving performance, achieving ease and\or reducing cost of implementation.

The foregoing discussion of the disclosure has been presented for purposes of illustration and description. The foregoing is not intended to limit the disclosure to the form or forms disclosed herein. In the foregoing Detailed Description for example, various features of the disclosure are grouped together in one or more embodiments for the purpose of streamlining the disclosure. This method of disclosure is not to be interpreted as reflecting an intention that the claimed disclosure requires more features than are expressly recited in each claim. Rather, as the following claims reflect, inventive aspects lie in less than all features of a single foregoing disclosed embodiment. Thus, the following claims are hereby incorporated into this Detailed Description, with each claim standing on its own as a separate preferred embodiment of the disclosure.

Moreover though the description of the disclosure has included description of one or more embodiments and certain variations and modifications, other variations and modifications are within the scope of the disclosure, e.g., as may be within the skill and knowledge of those in the art, after understanding the present disclosure. It is intended to obtain rights which include alternative embodiments to the extent permitted, including alternate, interchangeable and/or equivalent structures, functions, ranges or steps to those claimed, whether or not such alternate, interchangeable and/or equivalent structures, functions, ranges or steps are disclosed herein, and without intending to publicly dedicate any patentable subject matter.

What is claimed is:

1. An engine, comprising:

a plurality of turbo-compressor spool assemblies, each turbo-compressor spool assembly comprising a compressor and a turbine attached by a common shaft and a first of the turbo-compressor spool assemblies is in fluid communication with a second of the turbo-compressor spool assemblies, at least one of the common shafts of a selected turbo-compressor spool assembly comprising a metallic compressor rotor and a ceramic turbine rotor connected by a metallic-to-ceramic attachment joint and a first bearing being positioned adjacent to the metallic compressor rotor and a second bearing adjacent to the ceramic turbine rotor;

a free power turbine driven by a gas flow output by at least one of the turbo-compressor assemblies; and

a combustor operable to combust a fuel and a gas output by one of the plurality of turbo-compressor spool assemblies, wherein:

when the engine is in operation, the ceramic turbine rotor of the selected turbo-compressor spool assembly operates in a no-failure regime of the ceramic material;

the ceramic-to-metallic attachment joint is located on the common shaft of the selected turbo-compressor spool assembly to be in a no-failure regime of the ceramic material, the location of the metallic-to-ceramic attachment joint being positioned between the first and second bearings on the common shaft, and

when the engine is in operation, the metallic-to-ceramic attachment joint operates at a temperature of no more than about 800° K.

2. The engine of claim **1**, wherein the turbine rotor of the selected turbo-compressor spool assembly operates at a temperature of at least about 1,200° K.

3. The engine of claim **1**, wherein the first bearing is an oil bearing and the second bearing is an air bearing, and wherein at least one of the following is true:

(i) the air and oil are substantially separated by a discourager; and

(ii) the air bearing has a larger inside diameter than the oil bearing.

4. The engine of claim **1**, wherein the first bearing is an air bearing and the second bearing is an oil bearing.

5. The engine of claim **1**, wherein the first and second bearings are air bearings and wherein at least a portion of the air in the air bearing is removed from a gas flow of the compressor of the selected turbo-compressor spool assembly.

6. The engine of claim **5**, wherein the air is directed between a labyrinth seal and a discourager and the common shaft.

7. The engine of claim **1**, wherein the first and second bearings are oil bearings.

8. The engine of claim **7**, wherein air is bled from a compressor air flow and is directed between two labyrinth seals and the common shaft to inhibit oil from leaking into a turbine rotor air flow.

9. The engine of claim **1**, wherein a ceramic portion of the common shaft of the selected turbo-compressor spool assembly is at least about 40% of a length of the corresponding common shaft.

10. The engine of claim **1**, wherein an outer diameter of a ceramic portion of the common shaft of the selected turbo-compressor spool assembly is substantially the same as an outer diameter of a metallic portion of the common shaft at the joint and wherein the metallic-to-ceramic attachment joint is brazed and comprises a connecting sleeve.

11. The engine of claim **1**, wherein an outer diameter of the ceramic portion increases by at least about 20% in proximity to the ceramic turbine rotor while the metallic portion remains substantially constant between the metallic-to-ceramic joint and the metallic compressor rotor.

12. An engine, comprising:

a plurality of turbo-compressor spool assemblies, each turbo-compressor spool assembly comprising a compressor and a turbine attached by a common shaft and a first of the turbo-compressor spool assemblies is in fluid communication with a second of the turbo-compressor spool assemblies;

a free power turbine driven by a gas flow output by at least one of the turbo-compressor assemblies; and

a combustor operable to combust a fuel and a gas output by one of the plurality of turbo-compressor spool assemblies, wherein a selected turbo-compressor spool assembly comprises a metallic compressor rotor and a ceramic turbine rotor connected by a metallic-to-ceramic attachment joint, wherein a first and second bearings are located along a common shaft of the selected turbo-compressor spool assembly, and wherein at least one of the following is true:

(i) a turbine rotor of a selected turbo-compressor spool assembly operates in a no-failure regime of the ceramic material and the metallic-to-ceramic attachment joint is located to be in a no-failure regime of the ceramic material;

(ii) the metallic-to-ceramic attachment joint is located between the first and second bearings;

(iii) a ceramic portion of the common shaft has a length of at least about 40% of a length of the shaft; and

(iv) respective diameters of the ceramic portion and a metallic portion of the common shaft are substantially the same in the vicinity of the metallic-to-ceramic attachment joint.

13. The engine of claim **12**, wherein (i) is true.

14. The engine of claim **12**, wherein (ii) is true.

15. The engine of claim **12**, wherein (iii) is true and wherein an outer diameter of a ceramic portion of the common shaft of the selected turbo-compressor spool assembly is substantially the same as an outer diameter of a metallic portion of the common shaft at the joint.

16. The engine of claim **12**, wherein (iv) is true.

17. A method, comprising:

providing a gas turbine engine, the gas turbine engine comprising a turbo-compressor spool assembly, the turbo-compressor spool assembly comprising a compressor and a turbine attached by a common shaft, a free power turbine driven by a gas flow output by the turbo-compressor assembly, and a combustor operable to combust a fuel and a gas output by the turbo-compressor spool assembly, the compressor comprising a metallic compressor rotor and the turbine comprising a ceramic turbine rotor connected by a metallic-to-ceramic attachment joint; and

when the gas turbine engine is in operation, maintaining the turbine rotor and the metallic-to-ceramic attachment joint in a no-failure regime of the ceramic material.

18. The method of claim **17**, wherein the turbine of the turbo-compressor spool assembly operates at a temperature of at least about 1,200° K and wherein the metallic-to-ceramic attachment joint operates at a temperature of no more than about 800° K.

19. The method of claim **17**, wherein a first bearing is positioned adjacent to the metallic compressor rotor and a second bearing is positioned adjacent to the ceramic turbine rotor and wherein the ceramic-to-metallic attachment joint is positioned between first and second bearings on the common shaft of the turbo-compressor spool assembly.

20. The method of claim **19**, wherein the first bearing is an oil bearing and the second bearing is an air bearing and wherein the air and oil are substantially separated by a discourager.

21. The method of claim **19**, wherein the first bearing is an air bearing and the second bearing is an oil bearing.

22. The method of claim **19**, wherein the first and second bearings are air bearings and wherein at least a portion of the air in the air bearing is removed from a gas flow of the compressor of the turbo-compressor spool assembly.

23. The method of claim **22**, wherein the air is directed between a labyrinth seal and a discourager and the common shaft.

24. The method of claim **19**, wherein the first and second bearings are oil bearings.

25. The method of claim **24**, wherein air is bled from a compressor air flow and is directed between two labyrinth seals and the common shaft to inhibit oil from leaking into a turbine rotor air flow.

26. The method of claim **17**, wherein a ceramic portion of the common shaft of the turbo-compressor spool assembly is at least about 40% of a length of the common shaft.

27. The method of claim **17**, wherein an outer diameter of a ceramic portion of the common shaft of the selected turbo-compressor spool assembly is substantially the same as an outer diameter of a metallic portion of the common shaft at the joint and wherein the metallic-to-ceramic attachment joint is brazed and comprises a connecting sleeve.

28. The method of claim **26**, wherein an outer diameter of the ceramic portion increases by at least about 25% in proximity to the ceramic turbine rotor while the metallic portion remains substantially constant between the metallic-to-ceramic joint and the metallic compressor rotor.

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